# Extreme ultraviolet source at 6.7 nm based on a low-density plasma

S41

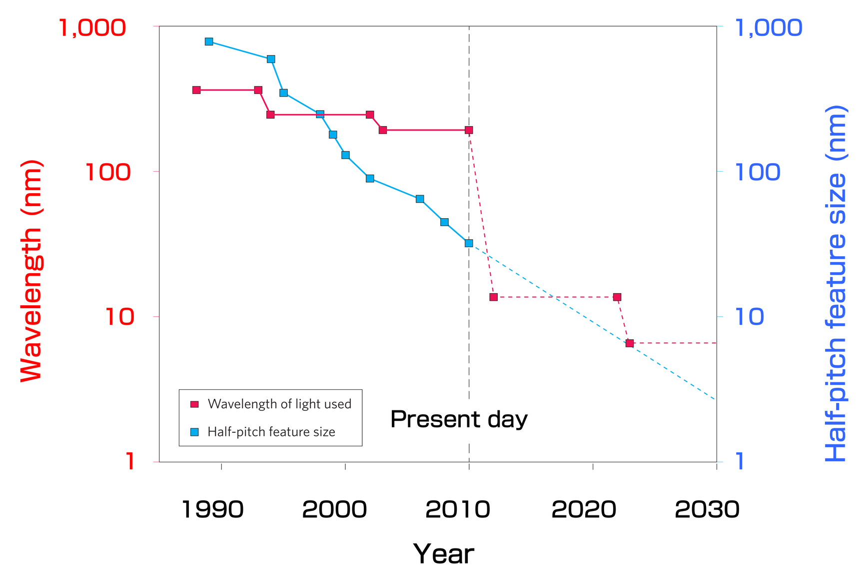
Takamitsu Otsuka[1], Takeshi Higashiguchi[1], Noboru Yugami[1], Bowen Li[2], Colm O'Gorman[2], Thomas Cummins[2], Deirdre Kilbane[2], Padraig Dunne[2], Gerry O'Sullivan[2], Weihua Jiang[3], and Akira Endo[4]

Utsunomiya University・CORE・CREST[1], University College Dublin[2], Nagaoka University of Technology[3], Waseda University[4]

Contact: takamitsu@plasma.ees.utsunomiya-u.ac.jp

## 1. Introduction

Wavelengths shorter than 10 nm are especially useful for next generation semiconductor lithography toward the final stage beyond the 13.5-nm EUV source and for other applications, such as material science and biological imaging near the water window. In particular, in our setup, EUV emission at the relevant wavelength is coupled with a Mo/$B_4C$ and/or La/$B_4C$ multilayer mirror with a reflective coefficient of 40% at 6.5−6.7 nm.




G. Tallents *et al.*, Nature Photonics **4**, 809 (2010).

***From ASML presentation shows as follows:***


(1) extensive (beyond 8 nm@~2017)
(2) **6.X nm choice: Best transmission & Easier Manufacturing**
(3) Source: New fuel is needed
(4) $R$ ~ 80% (cal), $R$ ~ 40% (exp)@La/$B_4C$ MLM
(5) ***Total throughput for 6.7 nm & 13.5 nm is comparable!!!***

Fig. 1. Recent reports about EUV sources for semiconductor lithography.

## 2. Experimental setup

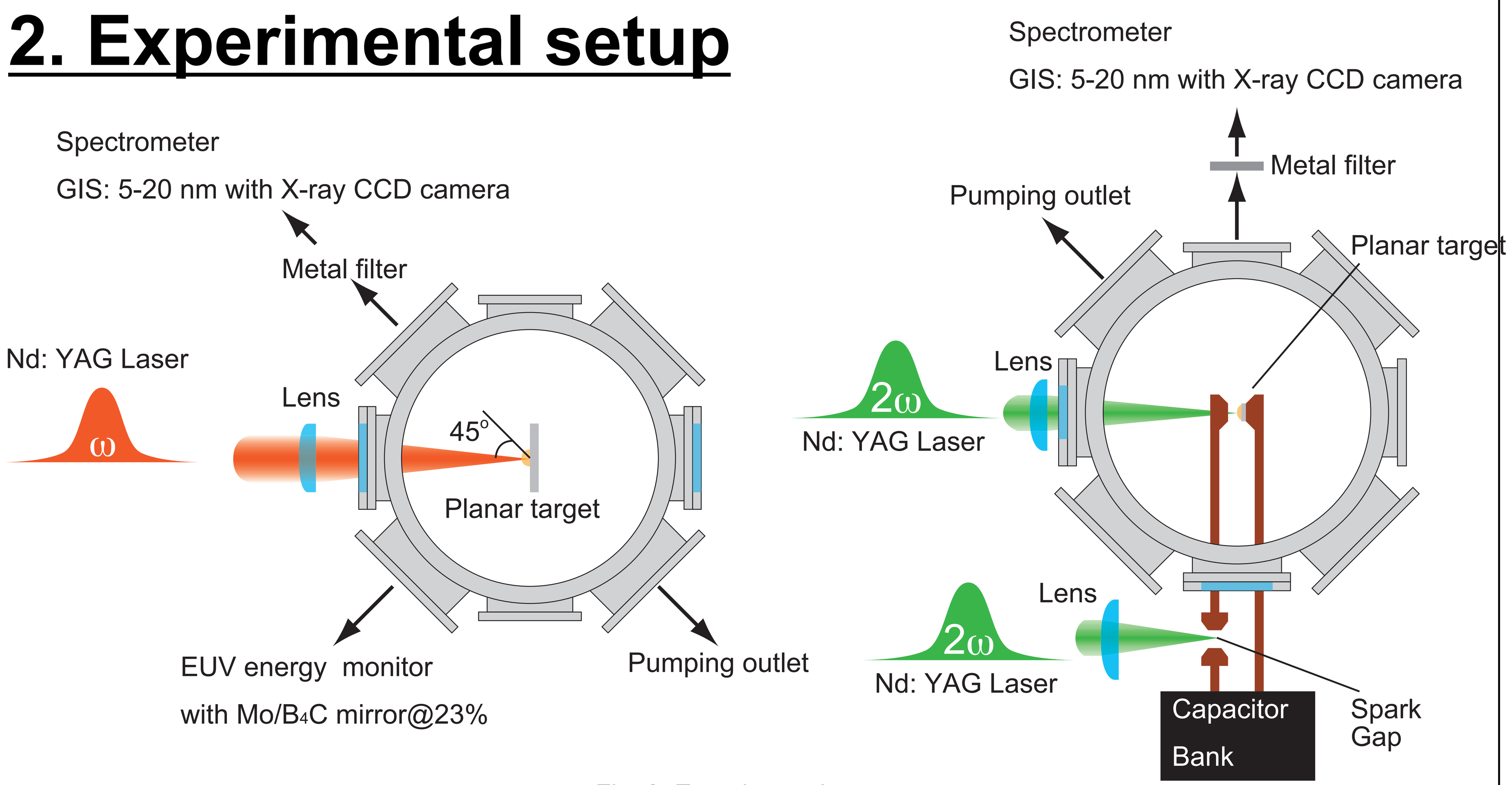
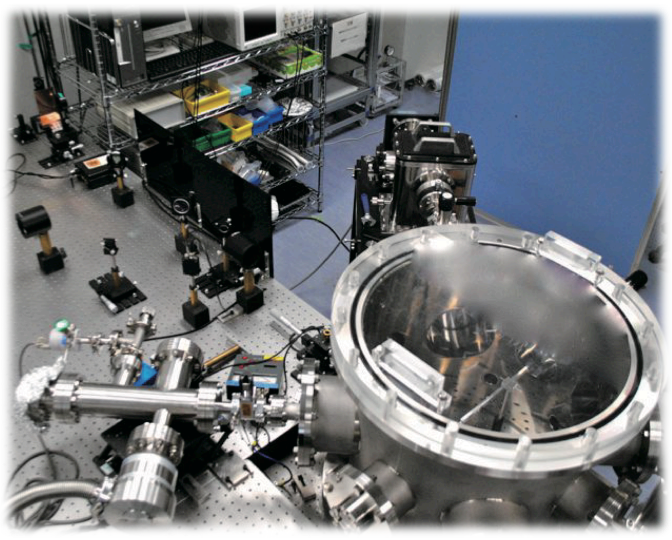



Fig. 2. Experimental setup.



**Laser-produced plasma**
Nd:YAG laser
Wavelength: 1064 nm
Maximum pulse energy: 400 mJ
Pulse width: 10 ns

**Discharged-produced plasma**

| Nd:YAG laser | Discharge system |
|---|---|
| Wavelength: 532 nm | Maximum discharge current: 12 kA |
| Maximum pulse energy: 1 J | Capacitance: 900 nF |
| Pulse width: 8 ns | |

## 3. Numerical and experimental results

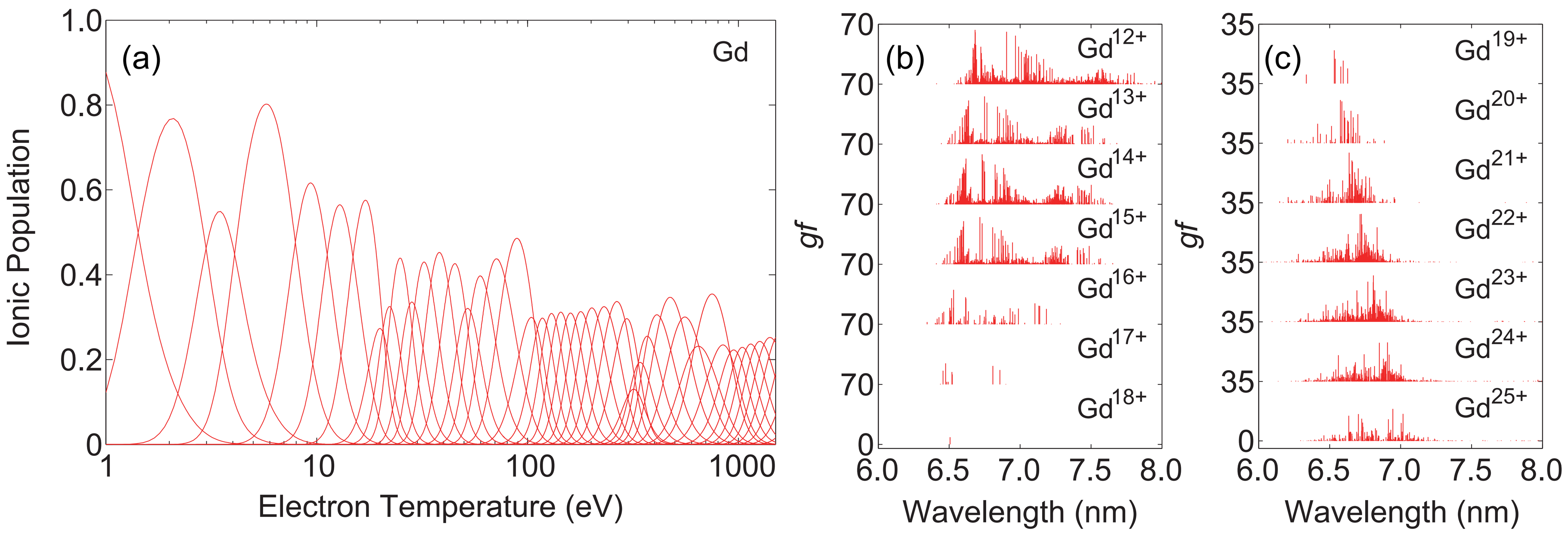



Fig. 3. Electron temperature dependence if the Gd (a) ion population according to the steady-state CR model. The weighted oscillator strength spectra of the resonant lines at for each contributing ion stage are shown in (b) and (c).

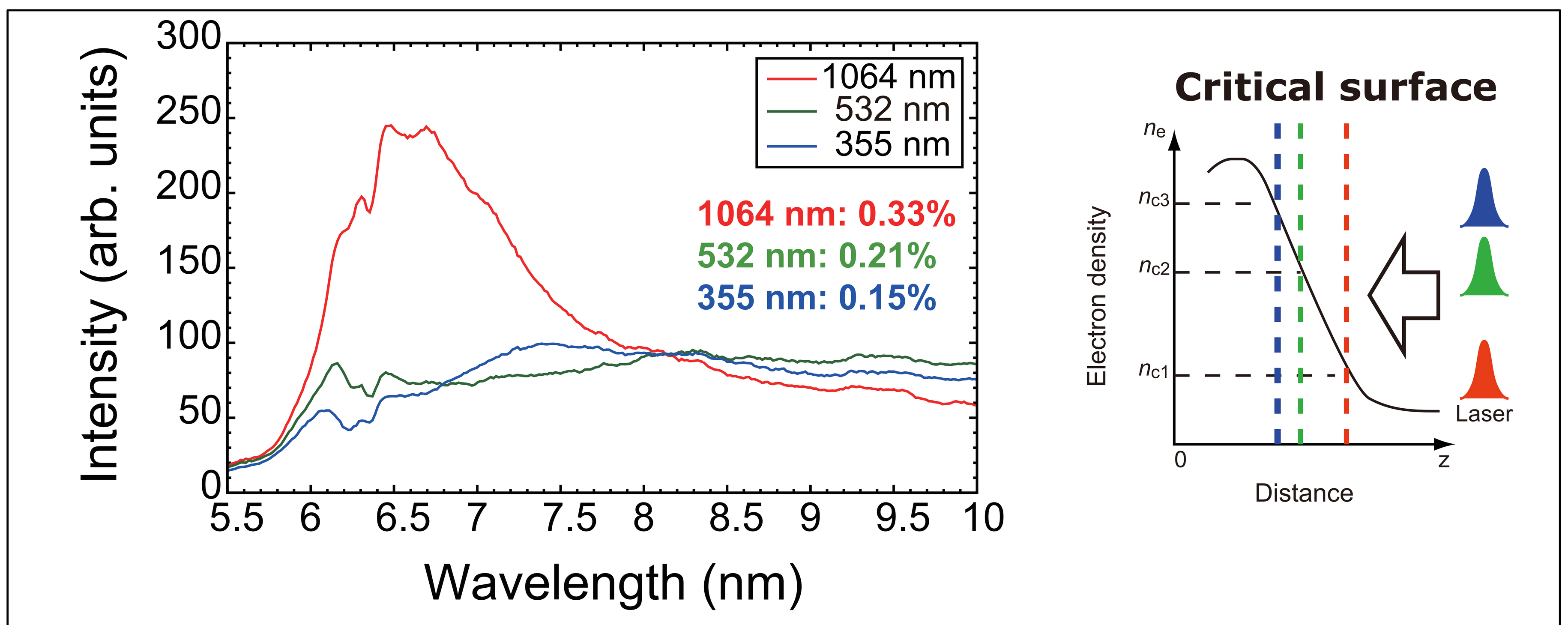



Fig. 4. EUV spectra at laser wavelengths of 1064 (red), 532 (green), and 355 nm (blue) for the same laser intensity of 1.6 × $10^{12}$ W/cm$^2$ (laser energy: 320 mJ per pulse and spot diameter: 50 μm (FWHM)), respectively.

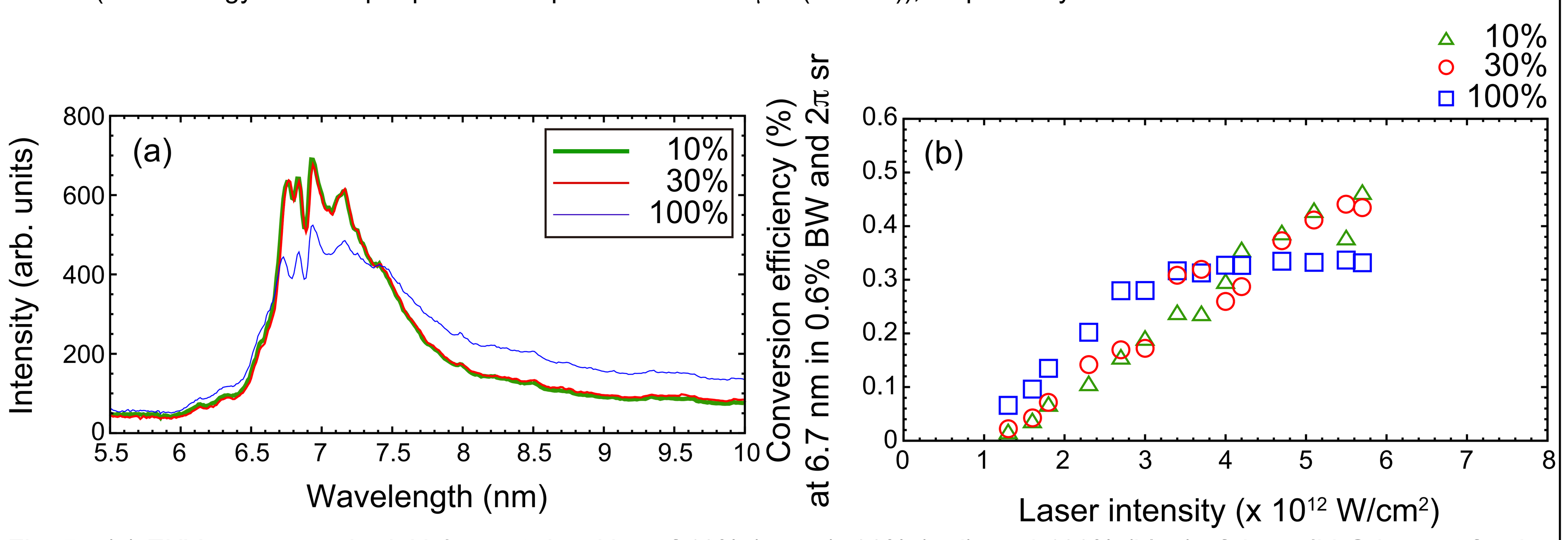



Fig. 5. (a) EUV spectra at the initial target densities of 10% (green), 30% (red), and 100% (blue) of the solid Gd target for the same laser intensity of 5.6 × $10^{12}$ W/cm$^2$ (laser energy: 400 mJ per pulse and spot diameter: 30 μm (FWHM)), respectively. (b) Laser intensity dependence of the EUV CE for a target containing 10% (green, triangles), 30% (red, circles), or 100% Gd (blue, rectangles).

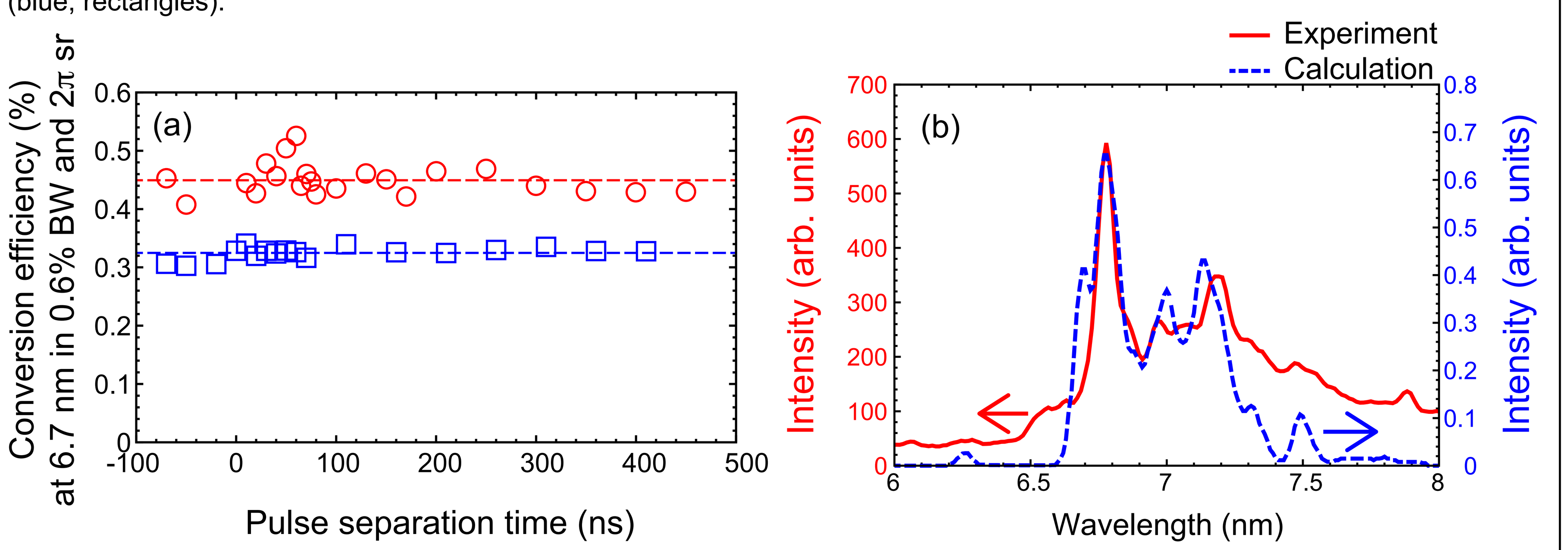



Fig. 6. (a) Pulse separation time dependence on the EUV CE in dual laser pulse irradiation for a target containing 30% (red, circles) or 100% Gd (blue, rectangles). The dashed lines correspond the single pulse without the prepulse for 30% (red) and 100% (blue). (b) EUV spectra from a laser-triggered DPP experiment and the numerical simulation.

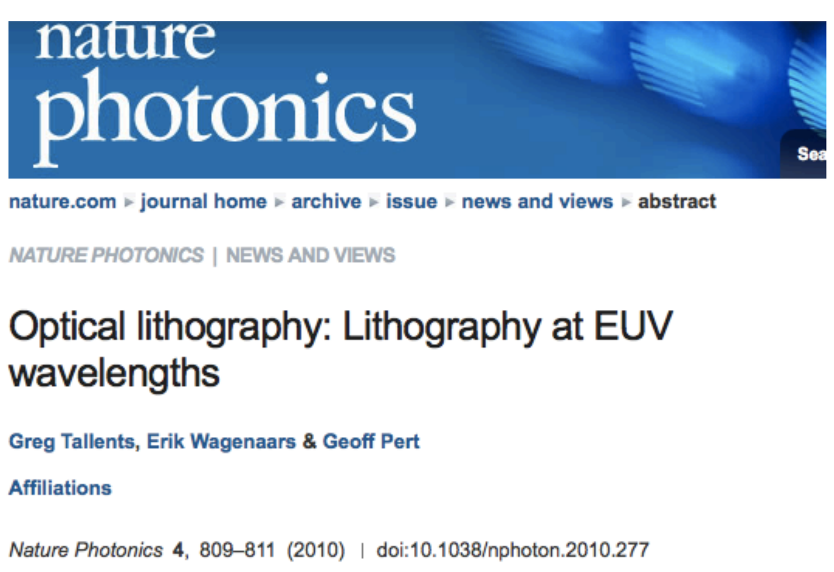
## 4. Summary

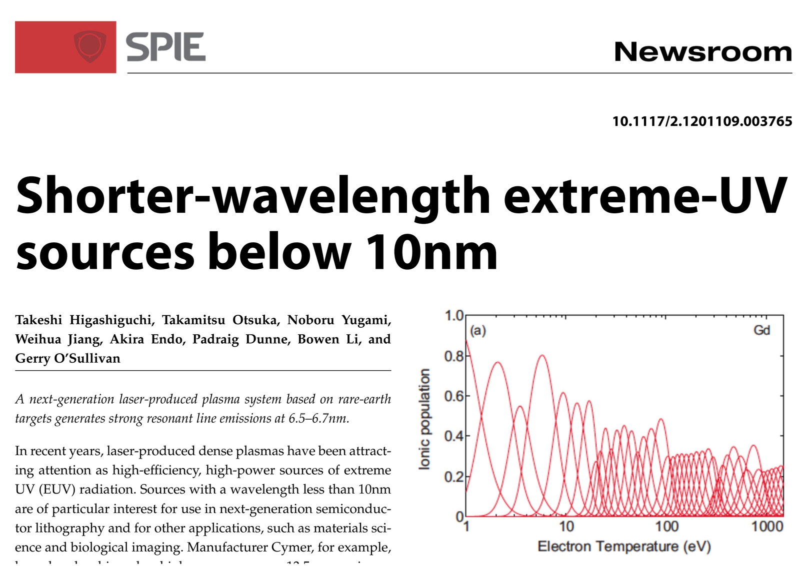
**We have demonstrated a laser-produced plasma extreme ultraviolet source around 6.5−6.7 nm using rare-earth targets of Gd.**

・As the effects of self-absorption on the resonance lines in the Gd plasmas are large, it is important to produce a low density plasma by use of long laser wavelength and/or low-initial target concentration of Gd.
・The spectrum based on the low initial density target was narrower and more intense than that of the pure solid target.
・The maximum CE was observed to be **0.54%.**

## References

[1] T. Otsuka *et al.*, Appl. Phys. Lett. **97**, 111503 (2010).
[2] T. Otsuka *et al.*, Appl. Phys. Lett. **97**, 231503 (2010).
[3] D. Kilbane *et al.*, J. Appl. Phys. **108**, 104905 (2010).
[4] G. Tallents *et al.*, Nature Photonics **4**, 809 (2010).
[5] T. Higashiguchi *et al.*, SPIE NewsroomDOI: 10.1117/2.1201109.003765 (2011).
[6] T. Higashiguchi *et al.*, accepted for publication in Appl. Phys. Lett. (2011).
[7] B. Li *et al.*, accepted for publication in Appl. Phys. Lett. (2011).




## Acknowledgements

A part of this work was performed under the auspices of MEXT (Ministry of Education, Culture, Science and Technology, Japan), "Utsunomiya University Distinguished Research Projects.", and "The Canon Foundation." One of the authors (T.H) also acknowledges support from Research Foundation for Opto-Science and Technology.
The UCD group acknowledges support from Science Foundation Ireland under Principal Investigator research grant 07/IN.1/B1771.

宇都宮大学 UTSUNOMIYA UNIVERSITY　MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN　キヤノン財団 The Canon Foundation　Sfi Science Foundation Ireland